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(54) **MATERIAL-DISCERNING PROXIMITY SENSING**

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(51) **Int. Cl.**

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See application file for complete search history.

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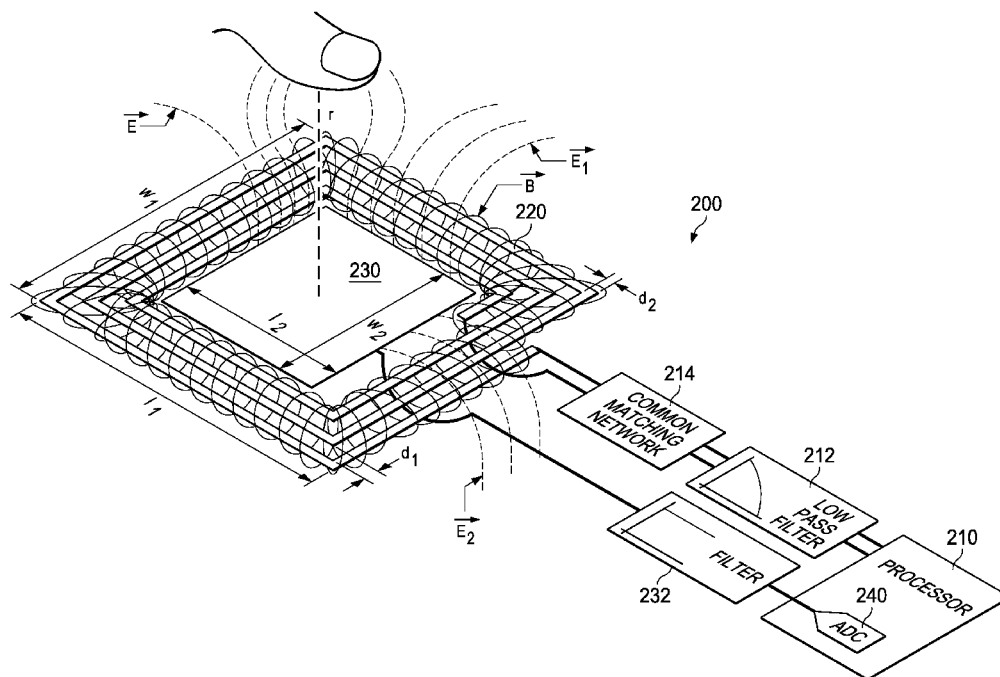*Primary Examiner* — Arleen M Vazquez

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(57) **ABSTRACT**

A material-discerning proximity sensor is arranged to include an antenna that is arranged to radiate a radio-frequency signal. A capacitive sensor is arranged to detect a change in capacitance of the capacitive sensor and to receive the radio-frequency signal. An electrical quantity sensor is arranged to detect a change of the received radio-frequency signal.
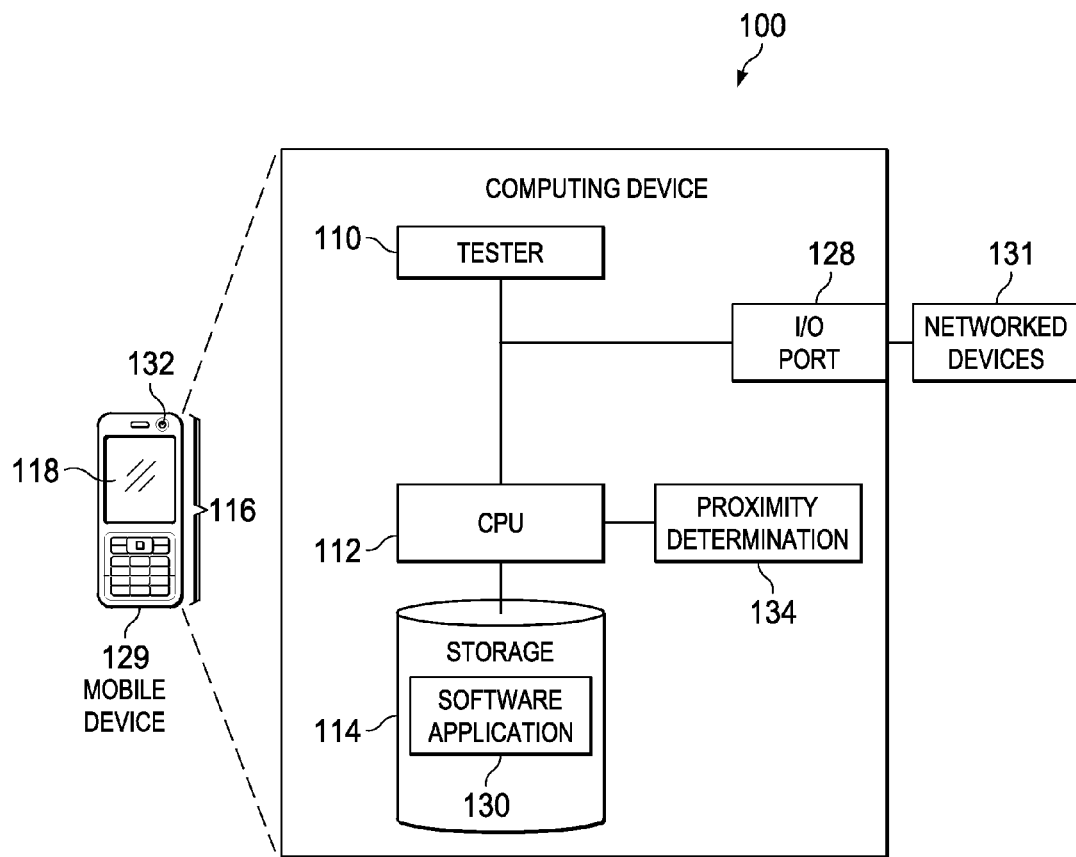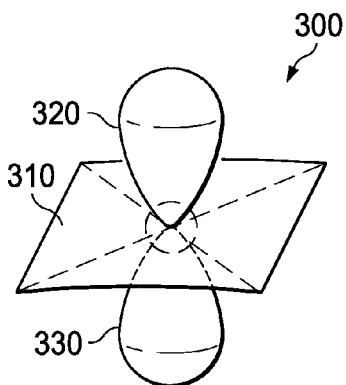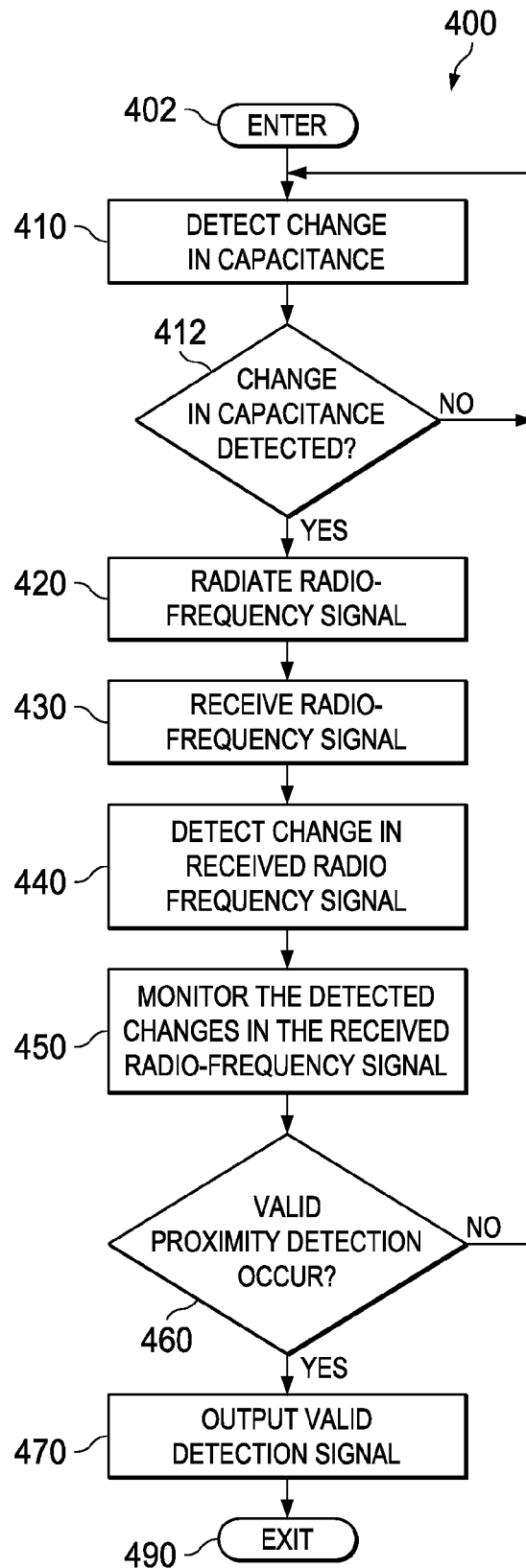
**11 Claims, 3 Drawing Sheets**

FIG. 1



FIG. 3

FIG. 2

400

402 — ( ENTER )

410 — DETECT CHANGE
IN CAPACITANCE

412 — CHANGE
IN CAPACITANCE
DETECTED? → NO

YES

420 — RADIATE RADIO-
FREQUENCY SIGNAL

430 — RECEIVE RADIO-
FREQUENCY SIGNAL

440 — DETECT CHANGE IN
RECEIVED RADIO
FREQUENCY SIGNAL

450 — MONITOR THE DETECTED
CHANGES IN THE RECEIVED
RADIO-FREQUENCY SIGNAL

VALID
PROXIMITY DETECTION
OCCUR? → NO

460

YES

470 — OUTPUT VALID
DETECTION SIGNAL

490 — ( EXIT )

**FIG. 4**

# MATERIAL-DISCERNING PROXIMITY SENSING

## CLAIM OF PRIORITY

This application for Patent claims priority to U.S. Provisional Application No. 61/641,972 entitled "PROXIMITY SENSING WITH DISCERNMENT OF MATERIALS" filed 3 May 2012, wherein the application listed above is incorporated by reference herein.

## BACKGROUND

Contemporary proximity sensing techniques are used to determine whether (and at what distance) an object has entered into a range of a proximity sensor of an autonomous electronic system. For example, a capacitive electrode is able to discern the proximal presence of an object and in response activate a function of the autonomous electronic system. However, conventional sensors often have difficulty determining the nature of the proximal object and/or the material(s) that comprise the object. Accordingly, false positive proximal detections often occur for certain objects that enter the range of the proximity sensor.

## SUMMARY

The problems noted above are solved in large part by material-discerning proximity sensing that includes an antenna that is arranged to radiate a radio-frequency signal. A capacitive sensor is arranged to detect a change in capacitance of the capacitive sensor and to receive the radio-frequency signal. An electrical quantity sensor is arranged to detect a change of the received radio-frequency signal.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an illustrative computing device in accordance with embodiments of the disclosure;

FIG. 2 is a schematic diagram illustrating a material-discerning proximity sensing system in accordance with embodiments of the disclosure;

FIG. 3 is a schematic diagram illustrating radiated lobes of a material-discerning proximity sensing sensor in accordance with embodiments of the disclosure; and

FIG. 4 is a flow diagram illustrating material-discerning proximity sensing in accordance with embodiments of the disclosure.

## DETAILED DESCRIPTION

The following discussion is directed to various embodiments of the invention. Although one or more of these embodiments may be preferred, the embodiments disclosed should not be interpreted, or otherwise used, as limiting the scope of the disclosure, including the claims. In addition, one skilled in the art will understand that the following description has broad application, and the discussion of any embodiment is meant only to be exemplary of that embodiment, and not intended to intimate that the scope of the disclosure, including the claims, is limited to that embodiment.

Certain terms are used throughout the following description—and claims—to refer to particular system components. As one skilled in the art will appreciate, various names may be used to refer to a component. Accordingly, distinctions are not necessarily made herein between components that differ in name but not function. In the following discussion and in the

claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus are to be interpreted to mean "including, but not limited to . . . ." Also, the terms "coupled to" or "couples with" (and the like) are intended to describe either an indirect or direct electrical (including electromagnetic) connection. Thus, if a first device couples to a second device, that connection can be made through a direct electrical (including electromagnetic) connection, or through an indirect electrical connection via other devices and connections.

FIG. 1 shows an illustrative computing device 100 in accordance with embodiments of the disclosure. For example, the computing device 100 is, or is incorporated into, a mobile communication device 129, such as a mobile phone, a personal digital assistant (e.g., a BLACKBERRY® device), a personal computer, automotive electronics, projection (and/or media-playback) unit, or any other type of electronic system.

In some embodiments, the computing device 100 comprises a megacell or a system-on-chip (SoC) which includes control logic such as a CPU 112 (Central Processing Unit), a storage 114 (e.g., random access memory (RAM)) and tester 110. The CPU 112 can be, for example, a CISC-type (Complex Instruction Set Computer) CPU, RISC-type CPU (Reduced Instruction Set Computer), or a digital signal processor (DSP). The storage 114 (which can be memory such as on-processor cache, off-processor cache, RAM, flash memory, or disk storage) stores one or more software applications 130 (e.g., embedded applications) that, when executed by the CPU 112, perform any suitable function associated with the computing device 100. The CPU 112 can include (or be coupled to) a proximity determination 134 unit, which includes various components arranged in a common (or separate) substrate as disclosed herein below.

The tester 110 is a diagnostic system and comprises logic (embodied at least partially in hardware) that supports monitoring, testing, and debugging of the computing device 100 executing the software application 130. For example, the tester 110 can be used to emulate one or more defective or unavailable components of the computing device 100 to allow verification of how the component(s), were it actually present on the computing device 100, would perform in various situations (e.g., how the components would interact with the software application 130). In this way, the software application 130 can be debugged in an environment which resembles post-production operation.

The CPU 112 comprises memory and logic that store information frequently accessed from the storage 114. The computing device 100 is often controlled by a user using a UI (user interface) 116, which provides output to and receives input from the user during the execution the software application 130. The output is provided using the display 118, indicator lights, a speaker, vibrations, image projector 132, and the like. The input is received using audio and/or video inputs (using, for example, voice or image recognition), and mechanical devices such as keypads, switches, proximity detectors, and the like. The CPU 112 and tester 110 is coupled to I/O (Input-Output) port 128, which provides an interface (that is configured to receive input from (and/or provide output to) peripherals and/or computing devices 131, including tangible media (such as flash memory) and/or cabled or wireless media. These and other input and output devices are selectively coupled to the computing device 100 by external devices using wireless or cabled connections.

As disclosed herein, material-discerning proximity sensing techniques allow an autonomous electronic system to more accurately determine the substance of a proximal object

by evaluating characteristics of materials that are included by the proximal object. Discernment of the characteristics of materials included by the proximal object is used to reduce (and/or eliminate) problems that are associated with false positive proximal detections.

FIG. 2 is a schematic diagram illustrating a material-discerning proximity sensing system in accordance with embodiments of the present disclosure. System **200** is an example autonomous electronic system that is arranged to perform material-discerning proximity sensing. System **200** includes a processor **210**, a low pass filter **212**, a, common matching network **214**, an antenna **220**, a capacitive proximity sensor **230**, a filter **232**, and an analog to digital (ADC) converter **240**.

Processor **210** is a processor such as CPU **112** that is generally arranged to control functions of system **200** in response to the closeness of the material characteristics of proximal object, such as a human finger. Processor **210** generates and/or controls a single- or dual-ended radio-frequency signal that is adapted to drive antenna **220**. The radio-frequency signal is a repetitive wave function, which can be a sine wave, a square wave, or other waveforms suitable for driving antenna **220**. For example, a square wave signal can be filtered by low pass filter **212** to pass a fundamental frequency (at a frequency such as 13.56 megahertz). Common matching network **214** is arranged to balance the impedance of the feed lines to the antenna **220** with the characteristic impedance of the antenna **220** itself.

In the illustrated embodiment, antenna **220** is arranged as a coil wherein the antenna, when energized, has an electrical core that extends through a portion of the surface of the capacitive proximity sensor **230**. The coil of antenna **220** can be arranged as, for example, a series of conductive traces that progressively wind or loop (one or more times) around an inner portion of the capacitive sensor. When the conductive traces are arranged in a rectilinear fashion, each segment (or group of segments) is shorter (or longer, depending on a direction in which the segments are traversed) such that the segments progressively "spiral" inwards to (or outwards from, depending on the direction in which the segments are traversed) the capacitive proximity sensor **230**. (In an alternate embodiment, the conductive traces can also be arranged using curved traces to form a curved spiral that is wound around the capacitive proximity sensor **230**.)

The conductive traces have a length "$l_1$" that is longer than the length "$l_2$" of the capacitive proximity sensor **230** and a width "$w_1$" that is wider than the width "$w_2$" of the capacitive proximity sensor **230**. Each segment of the conductive traces is separated (e.g., by a dielectric) from an adjacent segment of the conductive traces by a distance "$d_1$" and has a width of "$d_0$." Thus the conductive traces are arranged to be mutually inductive and form an electrical field in response to an applied (e.g., time invariant) radio-frequency signal (coupled from the processor **210**, for example) being coupled to opposite end of the conductive traces. The conductive traces need not lie in the same plane as the capacitive proximity sensor **230**, need not surround the capacitive sensor, and even have various shapes, but are arranged to electrically interact with the capacitive proximity sensor **230**.

The total length of the conductive traces (as well as the number of "turns," the separation between adjacent segments, and width and length of each of the segments) can be selected in accordance with a fraction of the wavelength of the radio-frequency signal (e.g., tone and/or carrier wave) coupled to the antenna **220**. The range "r" and directionality of the radiated electric field are also affected by the shape, proportions,

trace width, distance between traces, total inner perimeter of the conductive traces and total outer perimeter of the conductive traces.

The electric field is illustrated using field lines $\vec{E}$, where field lines $\vec{E1}$ are generated in association with a capacitive sensor mode and field lines $\vec{E2}$ are generated in association with a radio frequency/material discernment mode. The field lines $\vec{E1}$ illustrate the electric field coupled between the object (to be detected) and the associated portions of the capacitive proximity sensor **230** and $\vec{E2}$ illustrate the electric field coupled between coil of antenna **220** and the associated portions of the capacitive proximity sensor **230**. An upper and lower main lobe of the electric and magnetic fields can be used to detect the object (to be detected) having range "r." The electric field is also associated with magnetic components $\vec{E}$. Both conductive and non-conductive objects can possibly impact the strength of the $\vec{E}$ field of the coil antenna, which is associated with field lines $\vec{E2}$. Thus, in the material discernment mode, as the $\vec{E}$ field is impacted, the $\vec{E2}$ field is thus also impacted, which causes a change in the amplitude on the associated portions of the capacitive proximity sensor **230** (due to the changes in the $\vec{E2}$ field), for example.

Thus, the antenna **220** is arranged as a coil that, when energized, generates an electrical field having upper lobes and lower lobes, with a main upper lobe and main lower lobe defining an axis that extends through a portion of the surface of the capacitive proximity sensor **230** (as discussed below with respect to FIG. **3**). When viewed as an orthogonal projection using an axis of projection (as viewed from above, for example) that is not parallel to a portion of the surface of the capacitive proximity sensor **230**, the traces appear to surround the capacitive proximity sensor **230**.

For ease of commercialization, the antenna that is arranged to radiate a radio-frequency signal can be driven using a transmit output power below the FCC threshold requiring certification (e.g., for a frequency band that includes the frequency of the radio-frequency signal coupled to the antenna **220**).

Capacitive proximity sensor **230** is, for example, a copper fill pad having an area determined as the (multiplication) product of the length "$l_2$" and the width "$w_2$" of the capacitive proximity sensor **230**. (The aspect ratio of a, for example, rectangular capacitive proximity sensor **230** can vary and the area thereof, for example, can be larger or smaller than the area of a human finger.) The copper fill pad of capacitive proximity sensor **230** is formed on a fixed substrate such as a printed circuit board (PCB) or formed on a flexible substrate such as a flexible PCB. As discussed above, in an embodiment coil antenna is arranged around the perimeter of the capacitive proximity sensor **230**.

The capacitive proximity sensor **230** is arranged to discern the proximal presence of an object by detecting a change in capacitance of the capacitive sensor. The capacitive proximity sensor **230** is also used as a sensor for the discernment of the material of the proximal object by sensing the disruption (and the degree of disruption) of the electric field produced by antenna **220**. Thus the capacitive proximity sensor **230** is used to make two differing types of measurements. In an embodiment, the measurements are time-multiplexed where the types of measurements are alternated.

System **200** uses the capacitive proximity pad in conjunction with an electrical quantity sensor such as an ADC (ana-

log-to-digital converter) to measure the level at the applied frequency of the electrical field coupled to the capacitive proximity sensor 230 from the surrounding coil antenna 220. A function of the electrical quantity sensor is to quantify (in units of time, resistance, capacitance, and the like) a detected electrical property that is associated with the capacitive proximity pad. As various objects move into the field of the antenna, they impact and interfere with the tuning and efficiency of the antenna 220 and the common matching network 214 (which can be matched to the antenna 220). Objects in the field that are conductive affect characteristics of the magnetic field (and the concomitant electric field) output by the antenna 220 to a substantially greater degree than non-conductive objects. One characteristic of the characteristics of the electric field that is changed is manifested as a change in amplitude of the radio-frequency signal used to generate the electric and magnetic fields coupled to the capacitive proximity pad.

The change in amplitude of radio-frequency signal can be detected by using measurements performed by the ADC 240. The ADC 240 forwards the measurements as data to be used by software and/or firmware of the processor 210. Filter 232 is optionally employed to filter the received radio-frequency signal to prevent and/or reduce aliasing of the sampled radio-frequency signal by the ADC 240.

In an embodiment, a low-speed ADC 240 is used to minimize power consumption, complexity, and layout area. With the low-speed ADC 240, under-sampling and aliasing are intentionally used in a manner that allows for signal energy at the ADC 240 input to be detected while providing increased immunity to noise.

Without external filtering (to maintain a low cost, for example), the amplitude of the received radio signal frequency can still be measured by the ADC 240 regardless of degree of aliasing caused by under-sampling (even given a large disparity in sampling rate and Nyquist rates with regards to the frequency of the radio-frequency signal). The capacitive proximity sensor 230 that is under-sampled by the ADC 240 thus effectively operates using a broadband input.

The total energy determined by the under-sampled ADC 240 input is determined by, for example, summing the magnitude of the samples of the capacitive proximity sensor 230 (as affected by the electric field) over a selected time period (e.g., a tenth of a second) in which to accumulate samples. (In an alternate embodiment, a software envelope detector can be arranged to determine the total energy.) Thus; an unperturbed electric field, the presence of a non-conductive object within the electric field, and the presence of noise content do not substantially affect the baseline level of energy at the ADC 240 input.

The amplitude of the sampled signal (even without the intervening presence of filter 232) is not substantially incorrectly measured by the ADC 240 when under-sampling the capacitive proximity sensor 230. The ADC 240 is able to substantially correctly measure the energy coupled to the capacitive proximity sensor 230 because the presence of a proximal conductive object (within range of the electric field) both lowers the energy (signal amplitude as determined by accumulating samples over a selected time period) at the input of the ADC 240, and also tends to shield the system 200 from external noise sources. Accordingly, under-sampling by the ADC 240 provides for increased noise immunity for the system, while also allowing the use of a relatively simple (e.g., low cost) broadband ADC 240 to measure the capacitive proximity sensor 230.

In other embodiments, more complex ADCs, comparators, sample and hold circuits, or other common peripherals or other various types of voltage sensors may be used to detect a change in amplitude of radio-frequency signal coupled to capacitive proximity sensor 230. The detected change in amplitude of radio-frequency signal coupled to capacitive proximity sensor 230 can be detected by accumulating samples over a selected time period using an electrical quantity sensor.

In an embodiment RFID (radio-frequency identification) signal generator is arranged to couple an RFID signal to the antenna 220 such that the antenna is used to radiate an RFID radio-frequency signal. Using the antenna 220 to radiate the RFID radio-frequency signal allows the system 200 design to be more compact as it obviates the need to have an antenna dedicated solely for radiating the RFID signal.

Likewise, the capacitive proximity sensor 230 is arranged to receive the RFID radio-frequency signal. Using the capacitive proximity sensor 230 is arranged to receive the RFID radio-frequency signal allows the system 200 design to be more compact by obviating the need to have a receiving antenna solely dedicated for receiving the RFID radio-frequency signal.

Similarly, the ADC 240 is arranged to sample the RFID radio-frequency signal received by the capacitive sensor and to output and to transmit the samples to the processor 210 to provide an RFID capability for system 200. Using the ADC 240 to sample the RFID radio-frequency signal allows the system 200 design to be more compact by sharing the use of the ADC for reading the RFID radio-frequency signal, reading the received radio-frequency signal, and measuring a capacitance of the capacitive proximity sensor 230, for example. The readings of the received radio-frequency signal, the received RFID radio-frequency signal, and the capacitance of the capacitive sensor can be time-multiplexed when transmitted to the processor 210, for example.

The selected time periods for reading of the received radio-frequency signal, the received RFID radio-frequency signal, and the capacitance of the capacitive sensor can vary in accordance with the selected reading function. For example, the time period for reading the RFID radio-frequency signal can be selected in accordance with the RFID protocols. Likewise, the time period for measuring the capacitance of the capacitive proximity sensor 230 can be selected in accordance with a time interval suitable for determining an RC (resistive-capacitive) time-constant associated with an implementation of the capacitive proximity sensor 230.

Similarly, the time period for readings of the received radio-frequency signal can be selected in accordance with a time interval suitable for determining the movement of a proximal object within the electric field. For a human finger moving within range "r" of a lobe of the magnetic and electric field, a selected time interval for accumulating samples can be selected to determine the velocity of the finger moving through a lobe of the electric field.

FIG. 3 is a schematic diagram illustrating radiated lobes of a material-discerning proximity sensing sensor in accordance with embodiments of the disclosure. As shown in FIG. 2, antenna 220 is arranged as a coil that, when energized, generates an electrical field in response to a radio-frequency signal being coupled the antenna 220. In FIG. 3, the electric field 300 is illustrated as a main "lobe" of the generated having an upper lobe 320 and a lower lobe 330, the upper lobe 320 and lower lobe 330 defining an axis that extends through a portion of the surface of the (flexible) capacitive sensor 310. The upper lobe 320 and the lower lobe 330 are illustrated as geometric shapes for the sake of simplicity. In various embodiments the shape of the electric field varies in accor-

dance with the various shapes and arrangements of the antenna **220** and the capacitive sensor **310**.

FIG. **4** is a flow diagram illustrating a material-discerning proximity sensing in accordance with embodiments of the disclosure. The program flow illustrated herein is exemplary, and thus various operations within the program flow can be performed in an order that is not necessarily the same as the program flow illustrated herein. Program flow begins at node **402** and proceeds to operation **410**.

In operation **410**, a change in the capacitance of the capacitive sensor is detected. The capacitive change is detected using any suitable method including, for example, measuring an RC time-constant that is associated with the capacitive sensor. As discussed above, the change in capacitance can detect the proximity of an object, but substantially fails to discern the material that comprises the object. Program flow proceeds to operation **412**.

In operation **412**, a determination is made whether a change in capacitance has been detected. If a change in capacitance has not occurred, program flow proceeds to operation **410**. If a change in capacitance has occurred, program flow proceeds to operation **420**.

In operation **420**, a radio-frequency signal is radiated by an antenna that is substantially arranged around a capacitive sensor. The antenna is substantially arranged around the capacitive sensor when the radiated radio-frequency signal induces a voltage in the capacitive sensor. Program flow proceeds to operation **420**.

In operation **430**, the capacitive sensor receives the radiated radio-frequency signal. A baseline measurement (such as when there is no object in the proximity of the capacitive sensor) of the magnitude of the received radio-frequency signal. The baseline measurement can be made by under-sampling (e.g., below Nyquist rates) the received radio-frequency signal using an ADC as described above to detect an energy level of the received radio-frequency signal received over a selected time period. The under-sampling also increases the relative amount of noise immunity of the system used to perform the material-discerning proximity sensing. The noise is typically generated externally to the system, although noise generated by the system is also possible. Program flow proceeds to operation **440**.

In operation **440**, a change in the received radio-frequency signal is detected. The change in the received radio-frequency signal is detected by measuring the magnitude of the received radio-frequency signal (using the under-sampling ADC, for example). Program flow proceeds to operation **450**.

In operation **450**, the detected changes in the received radio-frequency signal are monitored. The detected changes in the received radio-frequency signal are monitored by comparing the measured magnitude with the baseline measurement to determine the degree of the detected change. The change in the received radio-frequency signal can also be detected by measuring the magnitude of the received radio-frequency signal and comparing the measured magnitude with a predetermined threshold to determine the degree of detected change. The change in the received radio-frequency signal can also be detected by measuring the magnitude of the received radio-frequency signal and comparing the measured magnitude with a list of one or more thresholds that compare with predetermined thresholds that each correspond to a type of material of an object (such as a human finger) that would be used to make a valid proximity detection. Program flow proceeds to operation **460**.

In operation **460**, a determination is made whether a valid proximity detection has occurred. Comparison of the measured magnitude of the received radio-frequency signal with

the predetermined thresholds provides an indication of the material that comprises a proximal object (e.g., that causes the detected change in capacitance). The measured magnitude is in direct proportion to the conductivity of the proximal object. Thus, discernment of a characteristic of the material that comprises the proximal object increases the likelihood of a valid detection. If a valid proximity detection has not occurred, program flow proceeds to operation **430**. If a valid proximity detection has occurred, program flow proceeds to operation **470**.

In operation **470**, a valid detection signal is output. The valid detection signal is output in response to the determination of a valid detection. The output valid detection signal is used by a processing system to perform an action in response to the valid detection of a proximate object (detected in response to a press of a human finger, for example). The action performed can be any action performable by a system such as accepting a security code, selection of an elevator control, dispensing a selected product from a machine, and the like. Program flow proceeds to node **490** and terminates.

The various embodiments described above are provided by way of illustration only and should not be construed to limit the claims attached hereto. Those skilled in the art will readily recognize various modifications and changes that could be made without following the example embodiments and applications illustrated and described herein, and without departing from the true spirit and scope of the following claims.

What is claimed is:

1. A material-discerning proximity sensing device, comprising:

an antenna that is arranged to radiate a radio-frequency signal;

a capacitive sensor that is arranged to detect a change in capacitance of the capacitive sensor and that is arranged to receive the radio-frequency signal; and

an electrical quantity sensor that is arranged to detect a change of the received radio-frequency signal;

wherein the electrical quantity sensor comprises an analog to digital converter arranged to quantify the detected change of the received radio-frequency signal using a sampling rate that is less-than-or-equal-to twice the frequency of a carrier wave of the radio-frequency signal.

2. The device of claim **1**, wherein the analog to digital converter is arranged to quantify the detected change of the capacitance of the capacitive sensor.

3. The device of claim **2**, wherein the analog to digital converter is arranged to output time-multiplexed readings of the received radio-frequency signal and the capacitance of the capacitive sensor.

4. The device of claim **1**, wherein the capacitive sensor is conductive material arranged having a surface.

5. The device of claim **4**, wherein the surface of the capacitive sensor is planar.

6. The device of claim **4**, wherein the antenna is arranged as a coil that, when energized, has an electrical core that extends through a portion of the surface of the capacitive sensor.

7. The device of claim **4**, wherein the antenna is arranged as a series of conductive traces on a substrate that surround an inner portion of the capacitive sensor when viewed as a two-dimensional projection using an axis of projection that is not parallel to a portion of the surface of the capacitive sensor.

8. The device of claim **4**, wherein the antenna is arranged as a coil that, when energized, generates an electrical and magnetic field having an upper lobe and a lower lobe, the upper lobe and lower lobe defining an axis that extends through a portion of the surface of the capacitive sensor.

**9**. The device of claim **8**, wherein the antenna is arranged to radiate a radio-frequency signal using a transmit output power below the FCC threshold requiring certification.

**10**. A method for material-discerning proximity sensing, comprising:

radiating a radio-frequency signal using an antenna;

detecting a proximity of an object by detecting a change in capacitance of a capacitive sensor;

receiving the radio-frequency signal using the capacitive sensor;

detecting a change of the received radio-frequency signal;

converting the change of the received radio-frequency to a digital signal, wherein a sampling rate of converting the change of the received radio-frequency to a digital signal is less-than-or-equal-to twice the frequency of a carrier wave of the radio-frequency signal;

monitoring detected changes of the digital signal;

detecting a characteristic of a material of the object based on the detected changes of the digital signal; and

outputting a detection signal in response to detecting the proximity of the object and detecting the characteristic of the material of the object.

**11**. The method of claim **10**, wherein the characteristic of the material of the object is a conductivity of the material of the object.

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